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PROFILE-DRAG COEFFICIENTS OF CONVENTIONAL AND LOW-DRAG

AIRFOILS AS OBTAINED IN FLIGHT

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NACA

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SUMMARY

The results of flight investigations of the profile drag of several carefully finished conventional and low-drag airfoils are presented. The results indicated that in all cases lower profile-drag coefficients were obtained with the low-drag than with the conventional airfoils over the range of lift coefficient tested and that, for comparable conditions of lift coefficient and Reynolds number, the low-drag airfoils may have profile-drag coefficients which are at least 27 percent lower than the profile-drag coefficients of the conventional airfoils.

INTRODUCTION

A number of flight investigations have been conducted by the National Advisory Committee for Aeronautics during the past several years to determine the profile drag of various conventional and low-drag airfoils. The purpose of this report is to present the principal results of these investigations in order to provide information that may be of assistance in judging the relative merits of conventional and low-drag airfoils.

AIRFOILS TESTED

The various airfoils tested were the NACA 27-212, NACA 35-215, NACA 66,2-2(14.7), NACA 64,2-(1.4)(13.5),

NACA 2414.5, N-22, and two Republic S-3 sections, one
11 percent thick and the other 13 percent thick. These
two sections are designated Republic S-3,11 and Repub-
lic S-3,13 in this paper. Flight tests of the
NACA 64,2-(1.4)(13.5) and the NACA 2414.5 airfoils are
reported in references 1 and 2, respectively. The pro-
files of the airfoils tested are shown in figure 1.
The NACA 27-212 and NACA 35-215 airfoil sections were
built into panels around the wings of the airplanes on
which they were tested. The others were sections of
the actual wings of the test airplanes. The arrangement
of the test panels and the spanwise positions of the
wing sections tested are shown in plan form in figure 2.
The airfoil designation NACA 64,2-(1.4)(13.5), which is
the test section of the NACA-NAA (North American Avia-
tion, Inc.) compromise low-drag wing, was based on the
maximum thickness and on the pressure-distribution
characteristics computed from the measured ordinates
of the test section. The designation NACA 66,2-2(14.7)
was similarly determined.

The NACA 2414.5, Republic S-3,11, Republic S-3,13,
and N-22 sections may be classified as conventional
airfoils and the NACA 64,2-(1.4)(13.5), NACA 27-212,
NACA 35-215, and NACA 66,2-2(14.7) sections, as low-
drag airfoils.

All the airfoils tested were carefully smoothed
and faired to eliminate perceptible protuberances due
to rivets, skin joints, and access doors. Surface
waviness, however, was present to various degrees on
the different airfoils. Surface waviness was measured
by use of a curvature gage of the type shown in fig-
ure 3 on the upper surfaces of the NACA 35-215 and
Republic S-3,13 airfoils and on the upper and lower
surfaces of the NACA 64,2-(1.4)(13.5), NACA 66,2-2(14.7),
and Republic S-3,11 airfoils. No waviness measurements
were obtained for the other airfoils.

The curvature-gage measurements on the NACA 35-215,
NACA 64,2-(1.4)(13.5), NACA 66,2-2(14.7), Republic S-3,11,
and Republic S-3,13 airfoils were made with the legs
of the gage spaced 1.2, 3.8, 4.0, 4.0, and 3.0 percent
of the section chord, respectively. In order to
present these measurements on a comparable basis, the
measurements on the NACA 35-215, NACA 64,2-(1.4)(13.5),
and Republic S-3,13 airfoils were reduced to values d

that a gage would give if the legs were spaced 4.0 percent of the section chord c. This reduction was made to the first order of approximation on the assumption that the readings of a curvature gage were proportional to the square of the leg spacing. The reduced measurements together with the measurements on the NACA 66,2-2(14.7) and Republic S-3,11 sections are presented in figure 4 as plots of d/c against s/c, where s is the distance along the surface from the leading edge. The dashed lines in figure 4 indicate the approximate curvature-gage readings that would be obtained if the surfaces were free of waviness.

It should be pointed out that wing distortion in flight may introduce waviness considerably different from that measured. This effect is probably adverse and may be expected to vary considerably with wing construction.

The destabilizing effect on the laminar boundary layer due to waviness of a given magnitude increases as the chordwise velocity gradient becomes less favorable (or more adverse). The chordwise velocity distribution for the various airfoils at a section lift coefficient c_l of 0.20 have therefore been included in figure 4. The velocity distributions were calculated for the undistorted airfoil profiles by the method of reference 3. The velocity distributions are given as a plot of the ratio U/U_o against s/c, where U is the local velocity outside the boundary layer and U_o is the free-stream velocity.

PROFILE DRAG

The profile-drag coefficients were evaluated from wake surveys of the various airfoils by the method of reference 4 and compressibility corrections were applied as in reference 5. In figure 5 the section profile-drag coefficients c_{d_o} and the corresponding Reynolds numbers R are plotted against section lift coefficient c_l. The Mach numbers of the tests were less than 0.55.

From figure 5 it may be seen that all the low-drag airfoils gave lower profile-drag coefficients than the

conventional airfoils over the range of lift coefficient
tested. The lowest profile-drag coefficient, a value
of 0.0040, was measured on the NACA 27-212 section at
a lift coefficient of 0.28 and a Reynolds number
of 7.4 × 10⁶. The NACA 27-212 airfoil, however, is not
considered a particularly desirable airfoil because, as
indicated by wind-tunnel tests, low drag is obtained
only over a relatively small range of lift coefficient
and the pressure gradient at the trailing edge is
unnecessarily severe. At Reynolds numbers in the range
from 15 × 10⁶ to 20 × 10⁶, now commonly encountered by
fighter-type aircraft, profile-drag coefficients
of 0.0045 and 0.0052 were measured on the NACA 66,2-2(14.7)
and NACA 64,2-(1.4)(13.5) airfoils, respectively. At
Reynolds numbers from 22 × 10⁶ to 31 × 10⁶, a profile-
drag coefficient of 0.0049 was obtained on the
NACA 35-215 airfoil.

The lowest profile-drag coefficient obtained on
the conventional wing sections was 0.0062 and was
measured on the Republic S-3,11. The lowest profile-
drag coefficients obtained on the other conventional
sections were 0.0067 for the Republic S-3,13 and 0.0066
for the NACA 2414.5. All these values were obtained at
low lift coefficients in the range of Reynolds number
from 15 × 10⁶ to 20 × 10⁶. On the N-22 section only
one value of profile-drag coefficient, 0.0070, was
obtained, which was at the relatively high lift coeffi-
cient of 0.50 and the low Reynolds number of 4.4 × 10⁶.

The results for the NACA 66,2-2(14.7) and Repub-
lic S-3,11 sections were obtained for the most nearly
comparable test conditions - that is, lift coefficient,
Reynolds number, and wing-surface preparation - and are
therefore best suited for the comparison of the profile-
drag characteristics of low-drag and conventional air-
foils. At a lift coefficient of 0.20 and a Reynolds
number of 16 × 10⁶ the profile-drag coefficients for
the NACA 66,2-2(14.7) and Republic S-3,11 sections were
0.0045 and 0.0062, respectively. The profile-drag coef-
ficient of the NACA 66,2-2(14.7) section is thus 0.0017,
or 27 percent, lower than the profile-drag coefficient
of the Republic S-3,11 section.

Unpublished tests in the NACA two-dimensional low-
turbulence pressure tunnel of a section approximating

the NACA 66,2-2(14.7) indicated a profile-drag coeffi-
cient of 0.0034 at a lift coefficient of 0.20 and a
Reynolds number of 16 × 10⁶. Similar tests (unpublished)
of NACA 230-series airfoils indicated a profile-drag
coefficient of 0.0063 for an NACA 23011 section at a
lift coefficient of 0.20 and a Reynolds number
of 9 × 10⁶. The Republic S-3 sections have pressure-
distribution characteristics that are very nearly those
of the NACA 230-series sections and may therefore be
expected to have the same drag characteristics. Inas-
much as the surfaces of the NACA 66,2-2(14.7) airfoil
tested in flight were carefully finished to give a very
low degree of waviness (figs. 4(g) and (h)), probably
comparable with that of the tunnel model, the con-
siderably greater drag measured in flight as compared
with the value obtained in the tunnel is believed to be
due to an increase in surface waviness associated with
wing distortion under air loads. The better agreement
between the flight and tunnel results for the conven-
tional sections may indicate that the position of
transition is so far forward on these sections that it
is not materially affected by an increase in surface
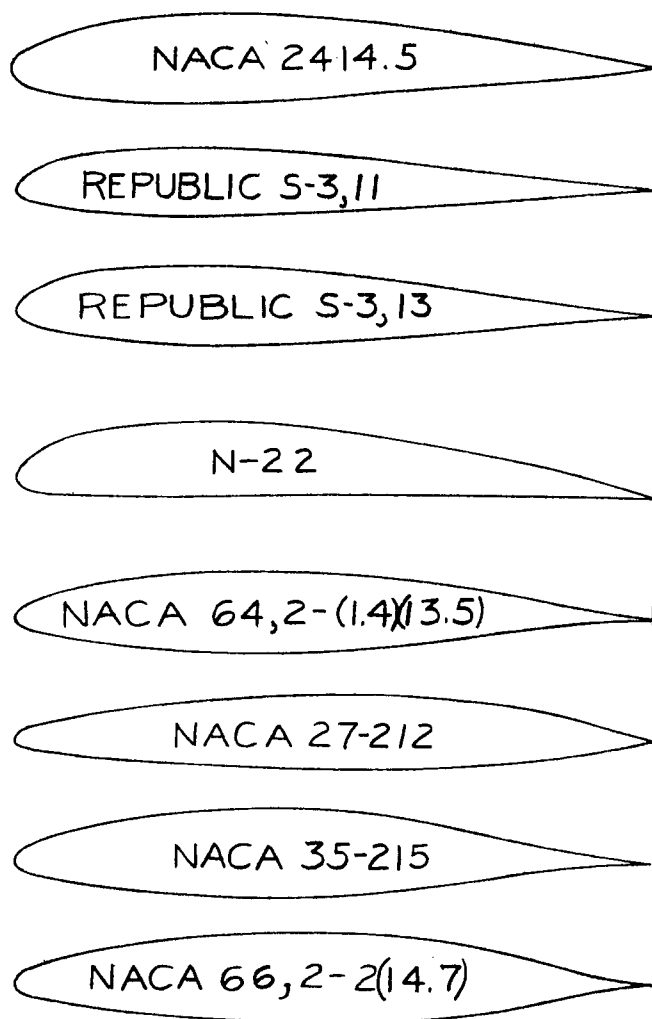waviness resulting from loads imposed on the wing in
flight.

CONCLUDING REMARKS

The results of profile-drag tests of various
smoothed airfoils indicated that in all cases lower
profile-drag coefficients were obtained on low-drag
airfoils than on conventional airfoils over the range
of lift coefficient tested. The results also indicated
that, for comparable conditions of lift coefficient and
Reynolds number, the low-drag airfoils may have profile-
drag coefficients which are at least 27 percent lower
than the profile-drag coefficients for the conventional
airfoils.

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NACA 24 14.5

REPUBLIC S-3, 11

REPUBLIC S-3, 13

N-2 2

NACA 64,2-(1.4)(13.5)

NACA 27-212

NACA 35-215

NACA 66,2-2(14.7)

Figure 1.- Profiles of various airfoil sections tested
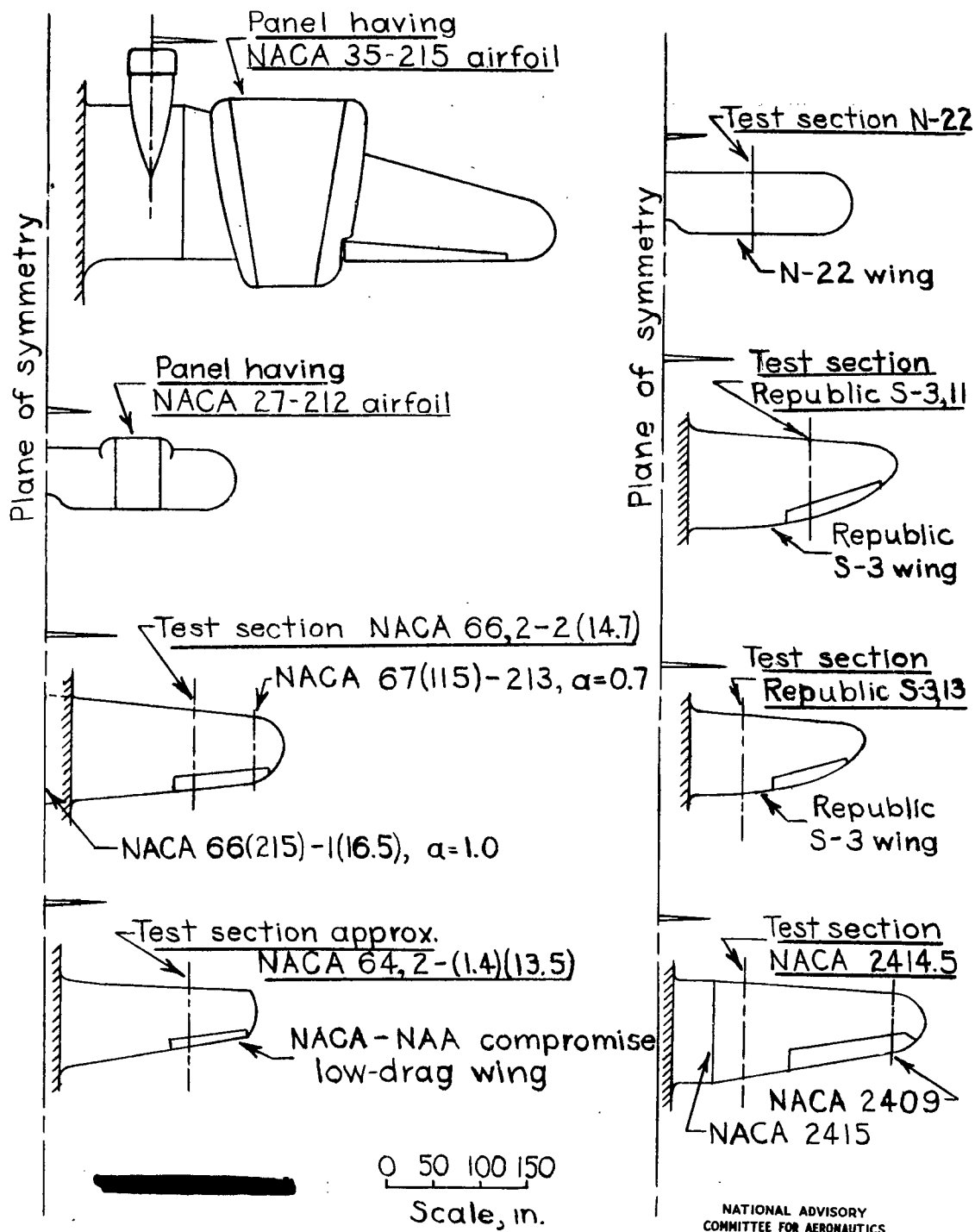in flight.

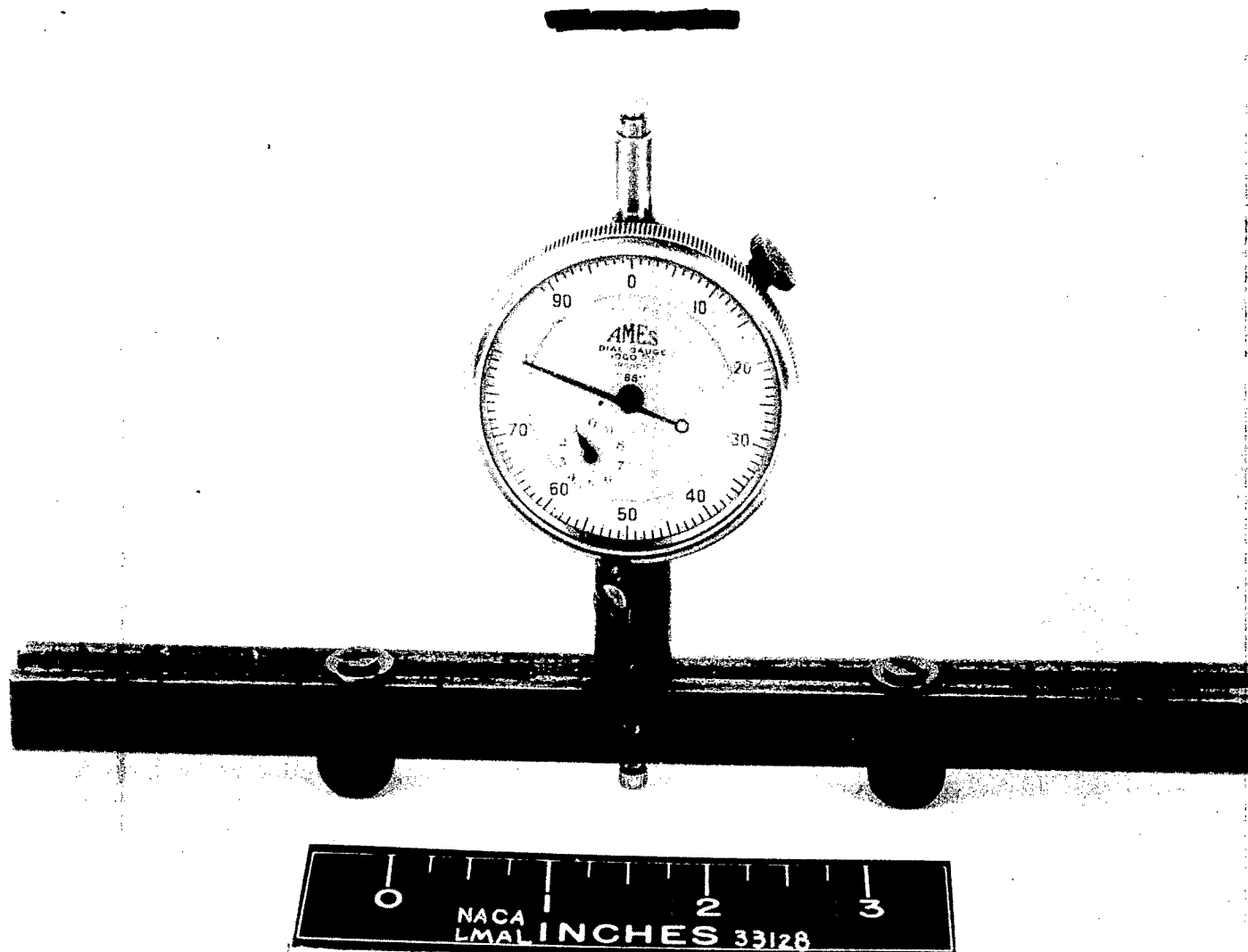Figure 2.- Plan forms of various wings of which tests were made.
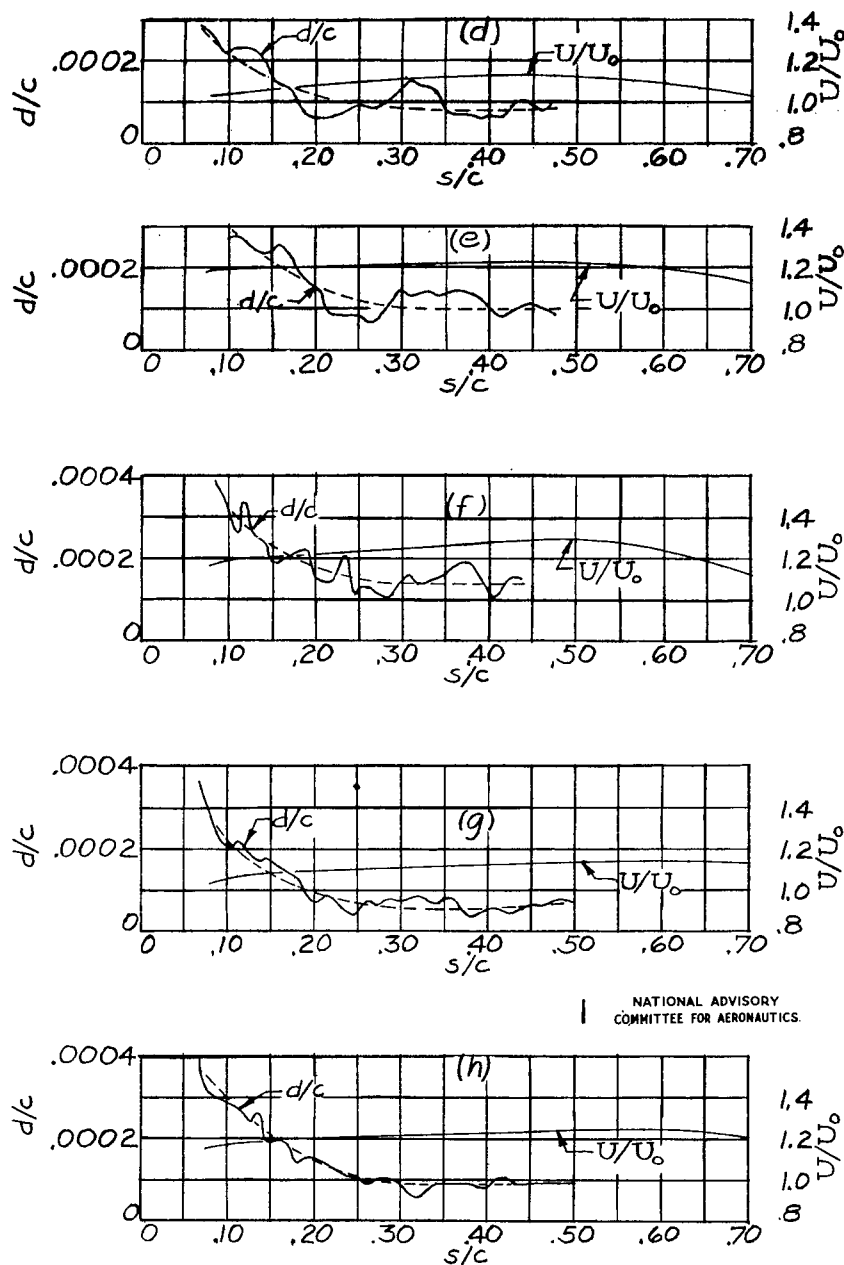
Figure 3.- Curvature gage.

Fig. 3

(d) NACA 64,2-(1.4)(13.5) airfoil, lower surface.
(e) NACA 64,2-(1.4)(13.5) airfoil, upper surface.
(f) NACA 35-215 airfoil, upper surface.
(g) NACA 66,2-2(14.7) airfoil, lower surface.
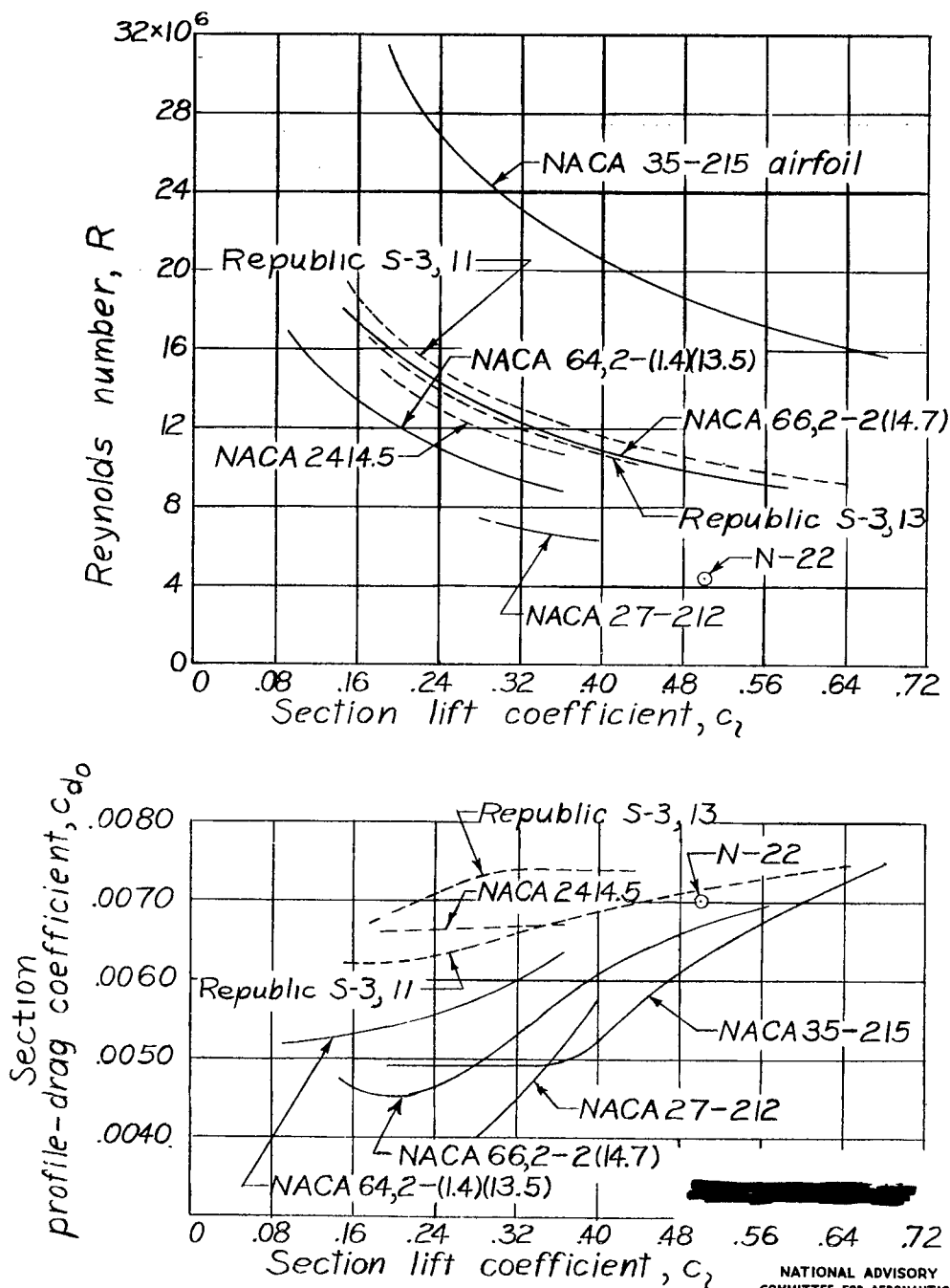(h) NACA 66,2-2(14.7) airfoil, upper surface.

Figure 4.- Concluded.

Figure 5.- Comparison of profile-drag coefficients ob-
   tained in flight on various conventional and low-drag
   airfoils. Reynolds number for corresponding lift
   coefficients given above.